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Drought events, spatial and temporal variability of rainfall in the Brazilian Pantanal

Eventos de seca, variabilidade espacial e temporal da chuva no Pantanal Brasileiro

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Abstract

The Brazilian *Pantanal* is home to a rich biodiversity, regulating the hydrological cycle and providing inputs for the local economy. Spatial and temporal variation in precipitation influences the ecological dynamics of the biome, and drought, aggravated by decreased rainfall, impacts water resources and biodiversity. In this context, the objective of this work is to analyze the spatial and temporal distribution of rainfall and drought in the Brazilian *Pantanal*, between 1994 and 2023. Precipitation variability and the incidence of hydrological droughts in the *Pantanal* were estimated using ERA5-Land (?) data from 1994 to 2023, with global coverage and 9 km resolution. These data are continuous and without gaps, providing a complete global series for analysis. The standardized precipitation index (SPI) was used to monitor droughts, with negative values indicating water insufficiency and positive values indicating water surplus. In this study, SPI-3 and SPI-12 were quantified, used to monitor droughts considering 3 and 12 accumulated months, providing an analysis without space-time gaps, with observations in short and long periods. Annual precipitation in the *Pantanal* varied between less than 1000 mm and more than 2500 mm, with higher accumulations before the year 2000 and a reduction afterwards, especially in the last five years (2019-2023). The period from 1994 to 2001 had uniform rainfall of 1500 to 2500 mm, while subsequent years, such as 2002 and 2004, presented greater variations. The SPI identified different periods of precipitation anomalies, for SPI-3, the years with the greatest droughts, in terms of severity, intensity and duration, were 2019, 2020, 2021 and 2023. SPI-12 revealed alternating periods of drought and humidity in the last 30 years, with an increase in the frequency of dry events in recent years, indicating a downward trend.

Keywords:
SPI, Extreme events, Geo-technologies, Biome.

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Resumo

O Pantanal Brasileiro abriga rica biodiversidade, atuando na regulação do ciclo hidrológico e fornecendo insumos para a economia local. A variação espacial e temporal da precipitação influencia a dinâmica ecológica do bioma, e a seca, agravada pela diminuição das chuvas, impacta os recursos hídricos e a biodiversidade. Neste contexto, o objetivo deste trabalho é analisar a distribuição espacial e temporal da precipitação pluviométrica e da seca no Pantanal Brasileiro, no período de 1994 a 2023. A variabilidade da precipitação e a incidência de secas hidrológicas no Pantanal foram estimadas usando dados do ERA5-Land de 1994 a 2023, com cobertura global e resolução de 9 km. Os dados são contínuos e livres de lacunas, fornecendo uma série completa global para análise. O índice padronizado de precipitação (SPI) foi empregado para monitorar secas, com valores negativos indicando insuficiência hídrica e positivos, excedente hídrico. Neste estudo foi quantificado o SPI-3 e SPI-12, utilizados para monitorar as secas considerando 3 meses e 12 meses acumulados, proporcionando uma análise sem lacunas espaço-temporais, com observações em curto e longo período. A precipitação anual no Pantanal variou entre menos de 1000 mm e mais de 2500 mm, com maiores acumulados antes dos anos 2000 e uma redução após, especialmente nos últimos cinco anos (2019-2023). O período de 1994 a 2001 teve chuvas uniformes de 1500 a 2500 mm, enquanto anos subsequentes, como 2002 e 2004, tiveram variações maiores. O SPI identificou diferentes períodos de anomalias de precipitação, para o SPI-3, os anos com maiores secas, em quesitos de severidade, intensidade e duração foram 2019, 2020, 2021 e 2023. O SPI-12 revelou períodos alternados de seca e umidade nos últimos 30 anos, com um aumento na frequência de eventos secos nos últimos anos, indicando uma tendência de redução.

Palavras-chave:
SPI, Eventos extremos, Geotecnologias, Bioma.

I. Introduction

The climate change is already considered a major challenge for humanity due to its multi-sectorial and global impacts (Abbass et al., 2022). With the increasing frequency and intensity of events, particularly rainfall anomalies, significant changes in the hydrological regime are expected in various regions of the planet. Among these events, droughts became particularly prominent, not only due to the intensification of its severity and duration but also because of the growing frequency of their annual occurrence, which directly affects water availability (Mehta et al., 2023).

Such changes result from the increasing instability of meteorological factors and have significant implications for water, energy, agricultural, and ecological security. In this context of climate change and hydrological pressures, the Brazilian *Pantanal*, recognized as one of the largest continuous wetland areas on the planet, takes a central role in environmental discussions. This biome performs essential ecosystem

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functions, such as regulating the regional hydrological cycle, carbon sequestration, nutrient cycling, and biodiversity conservation. Additionally, it provides freshwater and supports multiple local and regional economic activities, solidifying its status as a strategic ecosystem across multiple ecological and socio-economic dimensions (Ivory et al., 2019).

Rainfall is one of the primary determinants of its ecological dynamics, exerting a direct influence on the flood pulse, primary productivity, and habitat distribution. However, this pattern exhibits high spatial and temporal variability, which underscores the need to understand it as a central element for the development of environmental management strategies. Droughts, in turn, represent the most significant natural disaster associated with climate variability on a global scale, with profound impacts on agriculture, energy production, water supply, and on the incidence of wildfires (Forootan et al., 2019; Wu et al., 2021).

These events are typically characterized by periods of precipitation below the climatological average, thereby disrupting the regional hydrological balance. Several studies have highlighted the critical role of rainfall sustaining the *Pantanal* ecosystems: Dias et al. (2017) investigated the spatial-temporal distribution of rainfall in the Mato Grosso State, including the Northern *Pantanal*; Ivory et al. (2019) examined how the annual precipitation variability influences the spatial distribution of vegetation in floodplain areas; and Marengo et al. (2021) found that prolonged drought events have led to wildfires that devastated hundred thousand hectares in the *Pantanal*. Nevertheless, further research is needed to focus on the relationship between precipitation and drought indices, such as the Standardized Precipitation Index (SPI).

Meteorological indices are the primary tools for identifying droughts across different temporal scales. The Standardized Precipitation Index (SPI) (Mckee et al., 1995) was developed to quantify, through numerical values, the severity and magnitude of droughts, thereby enabling the identification and interpretation of drought events or characteristics (Gonçalves et al., 2021).

From this perspective, the study of climatic conditions is a fundamental first step to understand the potential effects of changes in meteorological variables (Song et al., 2022). A detailed analysis of the spatial rainfall and drought in the Brazilian *Pantanal* is essential for the sustainable management of watercourses and the conservation of its biodiversity. Additionally, this type of analysis provides critical insights to support the development of public policies and climate change adaptation strategies.

In this context, this study analyzes the spatial and temporal variability of rainfall in the Brazilian *Pantanal* between 1994 and 2023, as well as the distribution of the estimated drought severity, using the SPI.

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The objective is to identify rainfall and drought patterns, thereby contributing to better understand the regional climate dynamics.

II. Materiais e Métodos

The spatiotemporal distribution of rainfall and the occurrence of meteorological and hydrological droughts were estimated for the *Pantanal* biome within Brazilian territory (Figure 1). The Pantanal biome is recognized as one of the largest wetland areas in the world, comprising an extensive floodplain covering 179,300 km², distributed across Brazil (78%), Bolivia (18%), and Paraguay (4%). In Brazil, the biome spans regions within the Mato Grosso (35%) and Mato Grosso do Sul States (65%) (Tomas et al., 2020; Marengo et al., 2021).

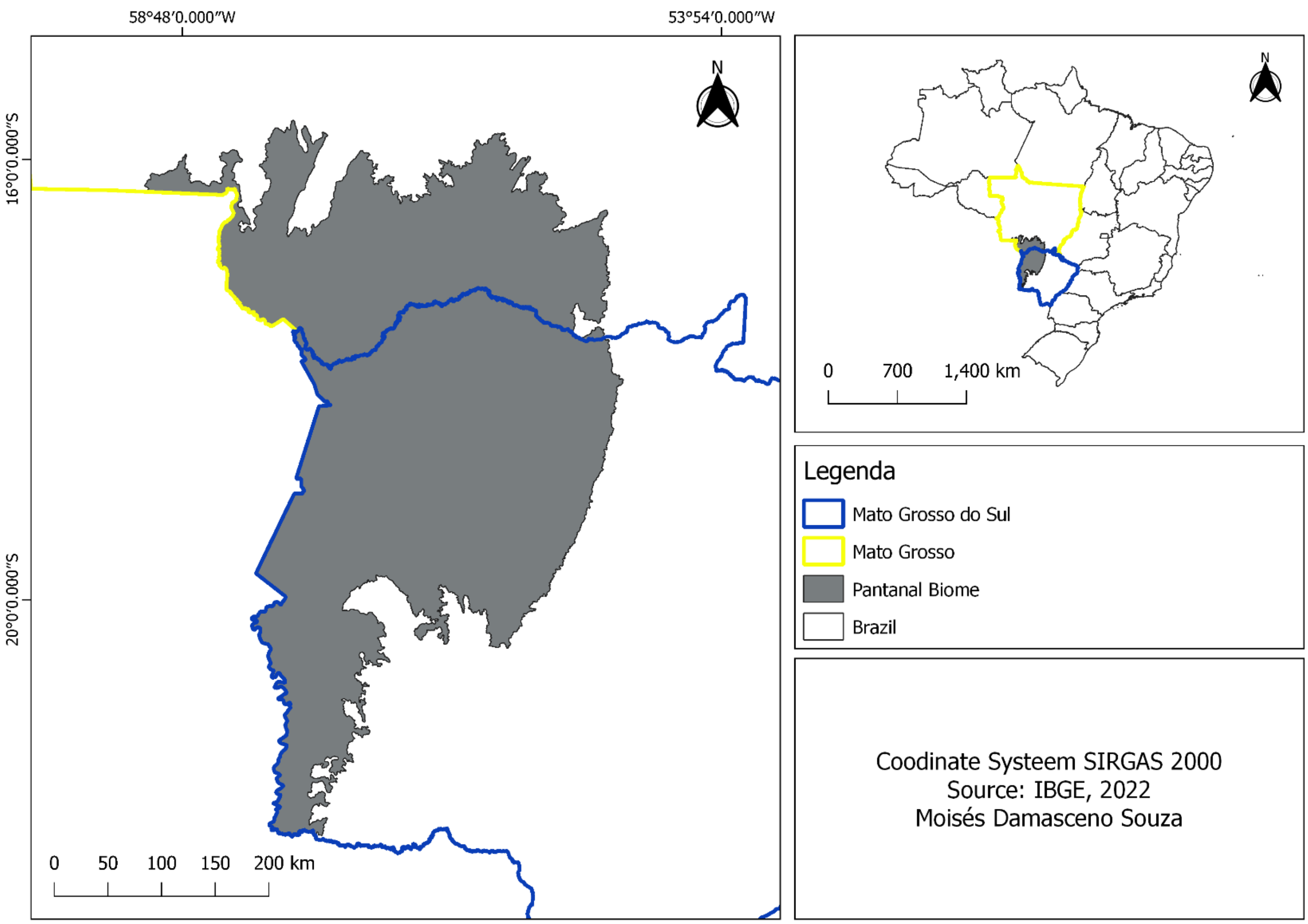

Figure 1 – The Pantanal in the Brazilian context. Source: IBGE (2022), prepared by the authors (2024).

Data and Processing

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The dataset used in this study was obtained from the Copernicus Climate Change Service (C3S), which is responsible for the ERA5-Land reanalysis (COPERNICUS, 2024). The European Centre for Medium-Range Weather Forecasts (ECMWF) launched the ERA5-Land dataset in 2019, providing improved quality for various land surface parameters compared to the previous ERA5 reanalysis. ERA5-Land offers enhanced resolution with 0.10° x 0.10° grid and data availability from 1950 to the present (Muñoz-Sabater et al., 2021; Lavers et al., 2022).

For this study, precipitation data from ERA5-Land was used, organized as daily records for the period from 1994 to 2023. To assess temporal distribution, the data were aggregated into monthly and annual indices using the R software (R Core Team, 2023). Subsequently, the SPI was applied to the precipitation data using the SPEI package (Beguería; Vicente-Serrano, 2023), available in R (https://cran.r-project.org/web/packages/SPEI/index.html). In this analysis, the SPI-3 index was adopted, which evaluates events based on a three-month accumulation period, making it suitable to characterize meteorological droughts (i.e., precipitation below climatological average).

The spatial analysis was conducted using Google Earth Engine (GEE) via script execution in the Code Editor, focusing on the distribution of precipitation and SPI within the geometry of the *Pantanal*. Initially, within the script, the total precipitation was calculated from January to December for each individual year (1994–2023) to obtain the annual totals. This process generated annual raster maps of precipitation distribution across the *Pantanal*. These products were subsequently converted into images using R software. To obtain the monthly distribution, each month in the historical series was analyzed separately, followed by the calculation of mean values for every month, resulting in 12 images (January - December).

The spatial assessment of drought events was also conducted and processed within GEE, using ERA5-Land precipitation data. To generate an image for each year, the SPI-12 index was applied, which is typically used in studies on hydrological droughts. This index evaluates drought events based on a 12-month accumulation period, and for all years analyzed, the period January to December was used as the reference for SPI-12 calculations. All scripts used in this study are available at: https://github.com/DamascenoSouza/Google-Earth-Engine/tree/main.

ERA5-land

The ERA5-Land reanalysis from ECMWF is characterized by the combination of model data with terrestrial observations from around the globe. This methodology integrates prior forecasts with recent observations, thereby producing a more accurate estimate of atmospheric conditions (Hu et al., 2019). These

141
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https://doi.org/10.5380/raega.v63i2.99705

datasets can provide consistent and gap-free records of multiple spatial and temporal variables, including precipitation data (Hersbach et al., 2020).

Recently there has been a significant progress in the development of various global reanalysis products. Within this context, numerous researchers have sought to assess the quality of these estimates across different regions of the world. For example, Gomis-Cebolla et al. (2023) conducted a study evaluating ERA5 and ERA5-Land reanalysis precipitation datasets in Spain, where these authors reported a good agreement between observed and reanalysis data, with Spearman correlation values ranging from 0.5 to 0.9 and RMSE between 2 and 8 mm/day.

Referring to the context of the *Pantanal* biome, some authors have already used these datasets to identify precipitation-related anomalies. For instance, Fernandes et al. (2024) conducted a study focused on drought quantification in the Mato Grosso State, using the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI), encompassing the Amazon, *Cerrado*, and *Pantanal* biomes within the State. Costa et al. (2023) also utilized ERA5-Land data to carry out a multi-scale analysis of droughts and heat waves in the Brazilian *Pantanal*.

Standardized Precipitation Index (SPI)

The SPI was used in this study to characterize major drought events (Mckee et al., 1993). This index assesses drought conditions considering only precipitation data. The SPI is recommended by the World Meteorological Organization for drought assessments, as its reliance solely on precipitation data enables a broad application in studies focused on water resource management (Pei et al., 2023).

The SPI is used for drought monitoring in various timescales and is calculated by normalizing the monthly precipitation through a probability distribution function, where negative values indicate water deficit in the region and positive ones represent water surplus (Fernandes et al., 2021; Liu et al., 2021; Lorenzo et al., 2024). The temporal scales used in SPI calculations correspond to the accumulation of precipitation over 1, 3, 6, 9, 12, 18, and 24 consecutive months (SPI-1, SPI-3, SPI-6, SPI-9, SPI-12, SPI-18, and SPI-24, respectively).

In this study, SPI-3 was applied for temporal analysis, considering the precipitation accumulated over three months. As previously mentioned, this analysis was conducted by extracting data from GEE and processing the SPI in R using the SPEI package (Beguería; Vicente-Serrano, 2023). For its spatial distribution, SPI-12 was estimated directly within GEE, encompassing data selection, processing, SPI application, and filtering. Subsequently, the figures were generated using the R software.

The determination of the SPI can be performed following equations 1 through 5.

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$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(a)} x^{\alpha-1} e^{\frac{x}{\beta}}, x > 0 \tag{1}$$

Where α is the shape parameter, β the scale parameter, x the precipitation volume, and the gamma function is defined as:

$$\Gamma(\alpha) = \int_0^{\infty} x^{\alpha-1} e^{-x} dx \tag{2}$$

The α and β indices are calculated using the maximum likelihood estimation.

$$\hat{\alpha} = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \tag{3}$$

$$\hat{\beta} = \frac{\bar{x}}{\hat{\alpha}} \tag{4}$$

$$A = ln(\bar{x}) - \frac{\sum \ln(x)}{n} \tag{5}$$

Where *n* is the number of precipitation series.

The probability is determined by equation 6.

$$G(x) = \int_0^{x} g(x)dx = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} \int_0^{x} x^{\alpha-1} e^{-x/\beta} dx \tag{6}$$

Thus, the SPI is calculated following equations 7 and 8.

$$SPI = S \frac{t-(c2t+c1)+c0}{[(d3t+d2)t+d1]t+1.0} \tag{7}$$

$$t = \sqrt{ln \frac{1}{G(x)^2}} \tag{8}$$

Thus, *x* is the amount of precipitation and *G(x)* is the probability distribution, *S* is the negative and positive coefficient of the distribution, where *G(x)* > 0.5, *S* = 1, and when *G(x)* ≤ 0.5, *S* = -1. The constants are *c*0 = 2.5155, c_1 = 0.8028, c_2 = 0.0103, d_1 = 1.4327, d_2 = 0.1892, and d_3 = 0.0013.

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The characterization of droughts, as well as the classification of the limits for each index, is presented in Table 1.

Table 1 – Classification of droughts according to the Standardized Precipitation Index (SPI).

Climate humidity categories	**SPI**
Exceptionally Wet	≥ 2,0
Severely Wet	1,60 a 1,99
Very Wet	1,30 a 1,59
Moderately Wet	0,80 a 1,29
Near Normal	0,79 a - 0,79
Moderately Dry	- 0,80 a - 1,29
Very Dry	− 1,0 a − 1,49
Severely Dry	− 1,60 a − 1,99
Exceptionally Dry	≤ − 2,0

Source: INPE, (2014).

III. Resultados e discussão

Temporal Analysis

The annual precipitation distribution for the *Pantanal* is characterized by fluctuations in accumulated indices both below and above the climatological average. Over the assessed period, the annual average for the region is 1,536.66 mm. Taking into account this value, eighteen years exceeded the average annual rainfall, representing 60% of the years evaluated. Thirteen years did not reach or exceed the annual average volume, including notable periods such as the years 2002 to 2005 and 2019 to 2023, with annual rainfall below the overall average (Figure 2).

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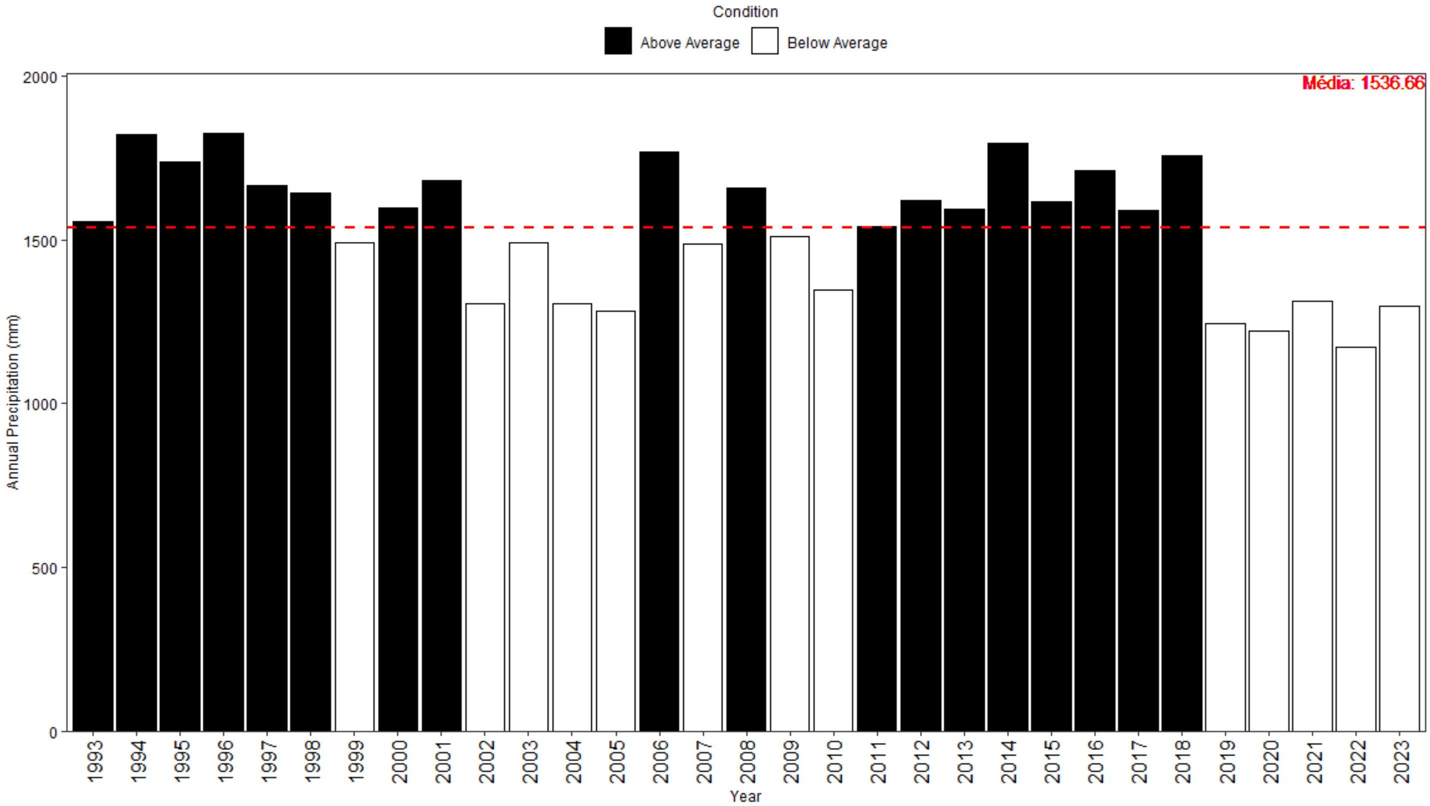

Figure 2 – Annual precipitation distribution from 1993 to 2023 for the *Pantanal*.

Similar results were observed by Marengo et al. (2016), who identified an annual climatological average of 1400 mm, with variation ranging from 800 to 1600 mm. In the same study, these authors emphasize that the region can reach an annual volume of 2000 mm. In this study, the highest values observed were in 1996 and 1994, with 1824.9 mm and 1820.2 mm, respectively, considering the period before the year 2000.

After the year 2000, the last year with an annual volume above the climatological average was recorded in 2018, with 1757.5 mm. In the subsequent years, a reduction in precipitation indices was observed, with values not exceeding 1350 mm annually. Studying the origin, dynamics, and forecasting of drought events in the Pantanal, *Thielen* et al. (2021) observed that the biome was affected by an extreme drought during the 2019–2020 period. They noted that the event evolved differently in space and time, affecting approximately 80% of the biome's territory, with duration longer than any drought previously recorded.

From an annual perspective, as mentioned, a sharp reduction in the annual precipitation regime occurred, with values ranging from 223 to 364 mm annually negative, within the 2019 to 2023 interval. These changes were also highlighted by Lázaro et al. (2020), who identified an increase in days without precipitation, as well as a reduction in the water mass. These authors characterized a reduction of 2 to 6% in days without

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precipitation per decade. For the year 1981, they identified 146 days without rain, reaching 248 and 287 in 2001 and 2011, respectively.

Monthly rainfall is distributed across two well-defined seasons: dry and wet. The dry season is characterized by a decrease in the monthly precipitation volume starting in May, with an average of 84 mm, a pattern observed until September. During this period, the rainfall volume does not exceed 100 mm per month. In the wet season, initial increases are sharp in October and extend until March, with monthly averages exceeding 100 mm (Figure 3).

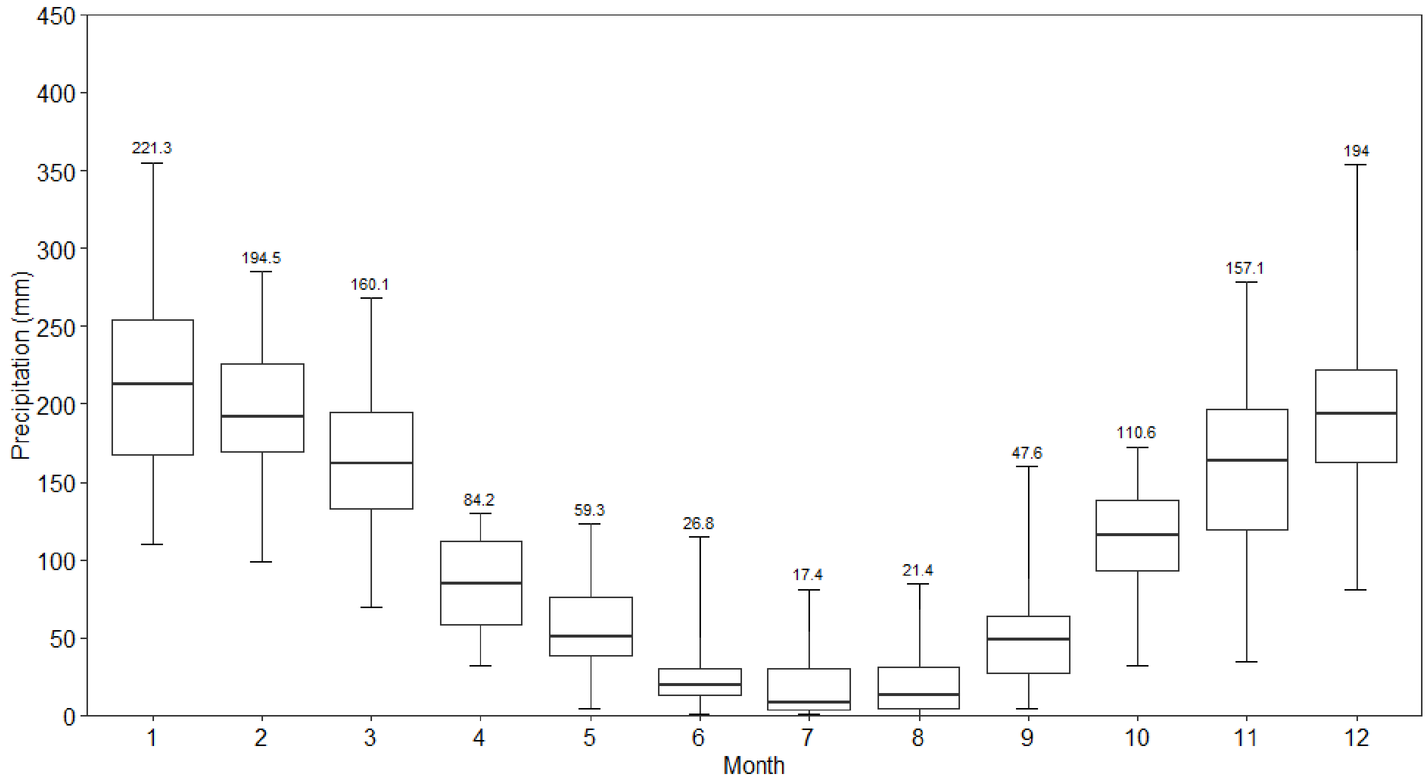

Figure 3 – Monthly distribution of rainfall from 1994 to 2023 for the *Pantanal*. The value above the boxplot represents the average.

These results corroborate the study from Marengo et al. (2021), who identified high seasonality in monthly precipitation, with a wet period from December to February, and a dry one from June to August. Similar to this study, they characterize the dry period with variations from 0 to 100 mm. Furthermore, there is a variation in the distribution of rainfall between the northern and southern sections of the *Pantanal*.

Regarding the variation in rainfall in the *Pantanal*, Costa et al. (2023), applying wavelet analysis to assess variations in the dry season, observed changes in the pattern of distribution of the wet and dry seasons, identifying delays and elongation in the seasons, a factor that can directly interfere with the flooding pulse and the dynamics of the biome.

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Considering a potential elongation or reduction in the seasons, Souza et al. (2024), in a study conducted in the northern *Pantanal* and western *Mato Grosso*, observed an elongation of the dry season in the region, with precipitation volumes lower than in previous decades. This result was reaffirmed through the application of the Man-Kendall Test, where the authors characterized a significant reduction in precipitation for May, July, August, September, and October, considering the time series from 1970 to 2023.

The *Pantanal* exhibits different precipitation regimes identified by the SPI-3, with fluctuations between wet and dry periods, especially after the year 2000. Considering the entire historical series, the main drought events are observed between the years 2003 to 2006 and from 2019 to 2023. In these intervals, there is little fluctuation towards wet periods, with the SPI-3 surpassing the -2.00 scale, classified as exceptionally dry, with a greater incidence of precipitation deficits for the biome (Figure 4).

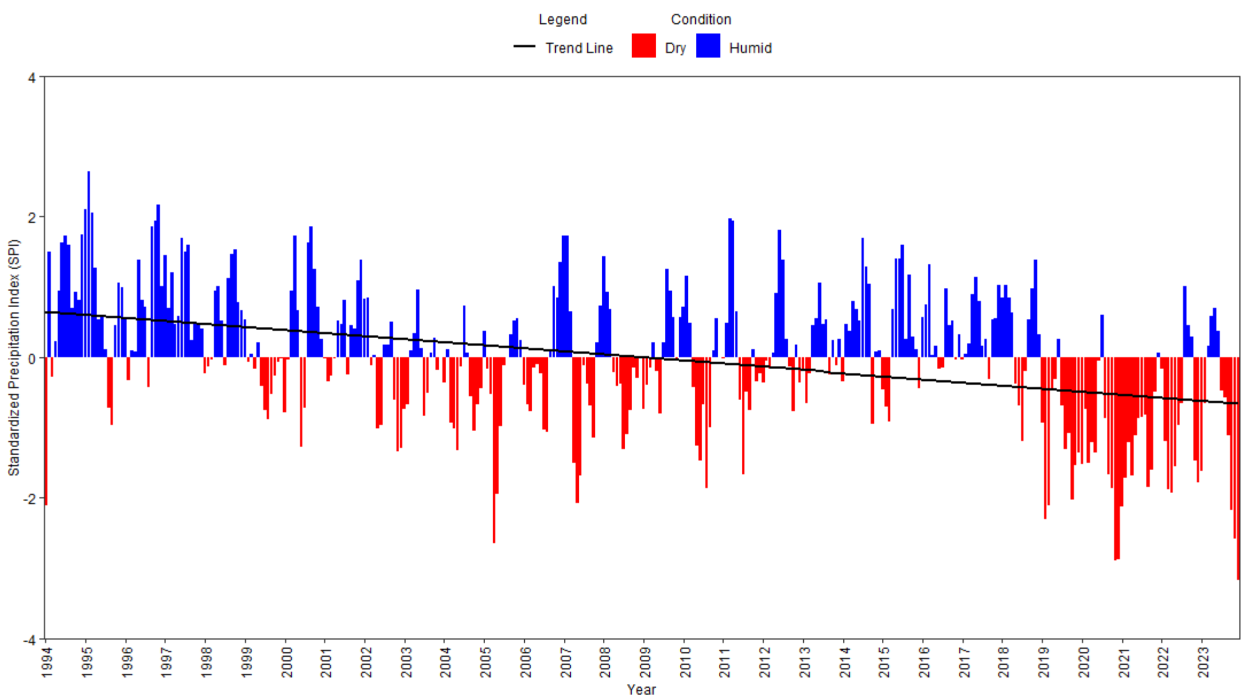

Figure 4 – Standardized Precipitation Index (SPI-3) from 1994 to 2023.

The higher propensity for drought events is also identified by the trend line, indicating a shift in behavior over the years from wet to dry conditions. When drought events are evaluated separately, seven years exceeded the -2.00 scale of the SPI-3. Except for 2005 and 1994, all events were characterized, starting in 2019, with a higher occurrence between the months of October and December. These results coincide with the annual precipitation distribution for the region, where a reduction in rainfall volume was identified in the last years of the study.

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These results corroborate the study by Fernandes et al. (2024), in which the authors, focusing on drought quantification, with an approach to the Amazon, *Cerrado*, and *Pantanal* biomes, identified negative trends for two indices: the SPI, using only precipitation data, and the SPEI, which takes into account atmospheric demand (ETP). The authors also observed that the most intense and severe events occurred in the *Pantanal* from 2019 onward, with the SPEI indicating extreme drought for two consecutive years.

Studying the extreme drought in the Brazilian *Pantanal* from 2019 to 2020, Marengo et al. (2021) characterized 2020 as the driest year since 1900. Furthermore, the authors identified significant changes in circulation and moisture flow across South America during the period of 2019 and 2020, leading to a blockage in the formation of convective storms. In the same study, a reduction in monthly precipitation, compared to the climatological average, was characterized, which may have contributed to the increased intensity of the drought during this period.

Spatial Analysis

The annual spatial distribution of precipitation for the *Pantanal* (Figure 5) is characterized by fluctuations in the annual totals, with rainfall volumes ranging from below 1000 mm to above 2500 mm across different portions of the biome. Considering the entire historical series from 1994 to 2023, with the temporal analysis, a higher total rainfall is observed in the years prior to 2000. After this period, some regions of the biome begin to show a reduction in annual rainfall volume, particularly in the central and southern parts of the *Pantanal*.

In this distribution, the highest accumulated value was recorded in 1996, exceeding 2400 mm, while the lowest annual total occurred in 2020, with values below 1000 mm in several portions of the biome. It is worth noting that there was a uniform rainfall regime between 1994 and 2001, with indices fluctuating between 1500 mm and 2500 mm, a pattern not observed in some subsequent years, such as 2002, 2004, and, with the greatest incidence of droughts, from 2019 onward, with an average annual precipitation below 1000 mm. Furthermore, considering only the period from 2019 to 2023, the northern region of the biome is the most affected by the reduction of the rainfall regime, particularly in the years 2020 and 2022, periods marked by the lowest totals in several zones of the region.

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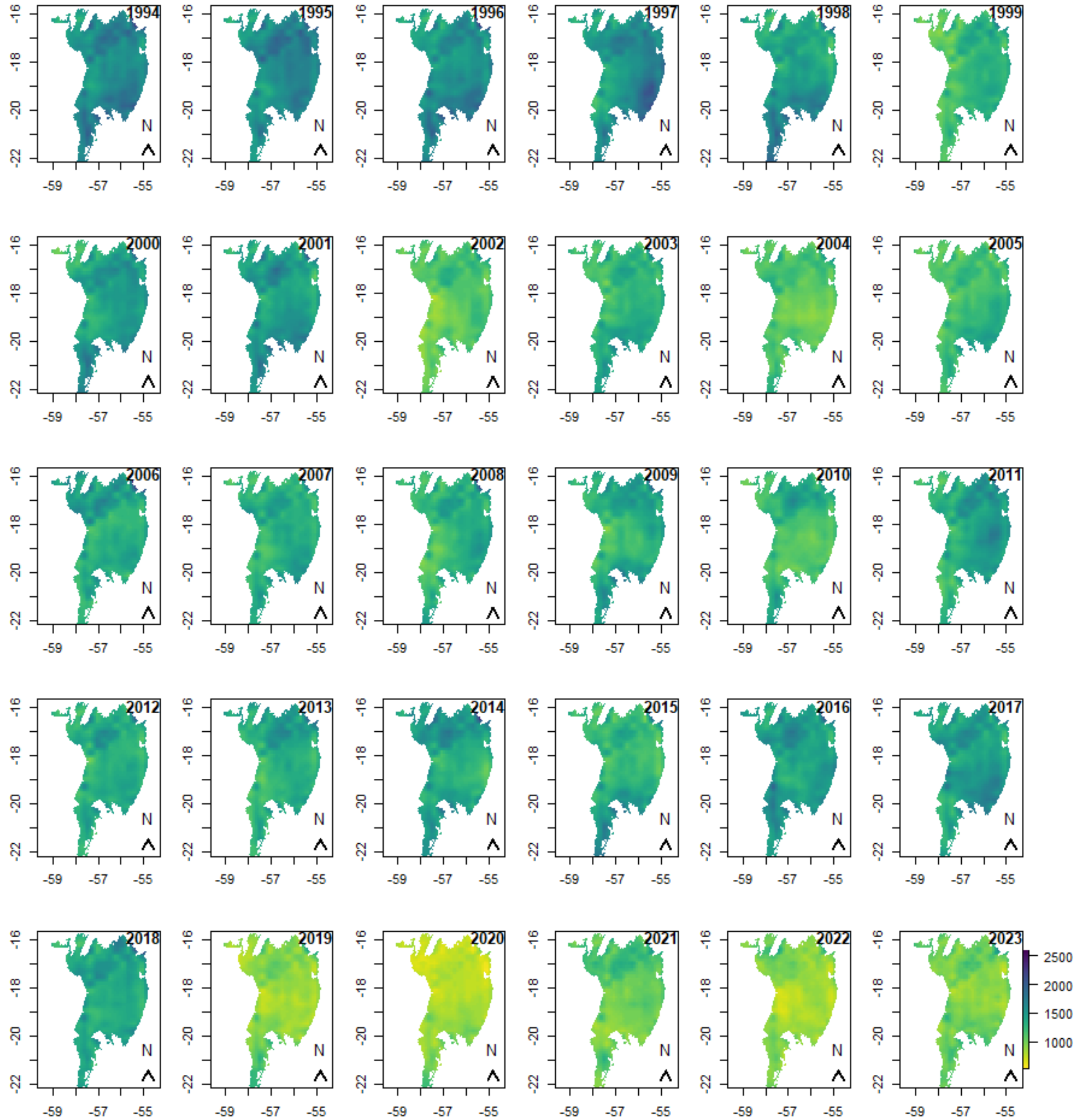

Figure 5 – Average annual spatial distribution of precipitation in the Brazilian *Pantanal* from 1994 to 2023.

These results are consistent with those observed by Tomasella et al. (2023), who assessed drought trends and impacts in Brazil, identifying significant trends toward drier conditions throughout central Brazil, particularly in the *Pantanal*. In line with the present study, which links the precipitation reduction indices of the *Pantanal,* Costa et al. (2023) observed that the Central-Western region of Brazil, including the *Pantanal*, experienced the worst drought of the last 50 years, with rainy seasons showing indices below the climatological average, considering only the period from 2019 to 2021.

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Monthly rainfall in the *Pantanal* is divided into two seasons: dry and rainy, with April and September representing the transition between these seasons, with decreases and increases in precipitation, respectively (Figure 6). The rainy season spans from October to March, with indices ranging from 150 to 350 mm per month, while the dry season sees cumulative precipitation below 100 mm, occurring from June to August.

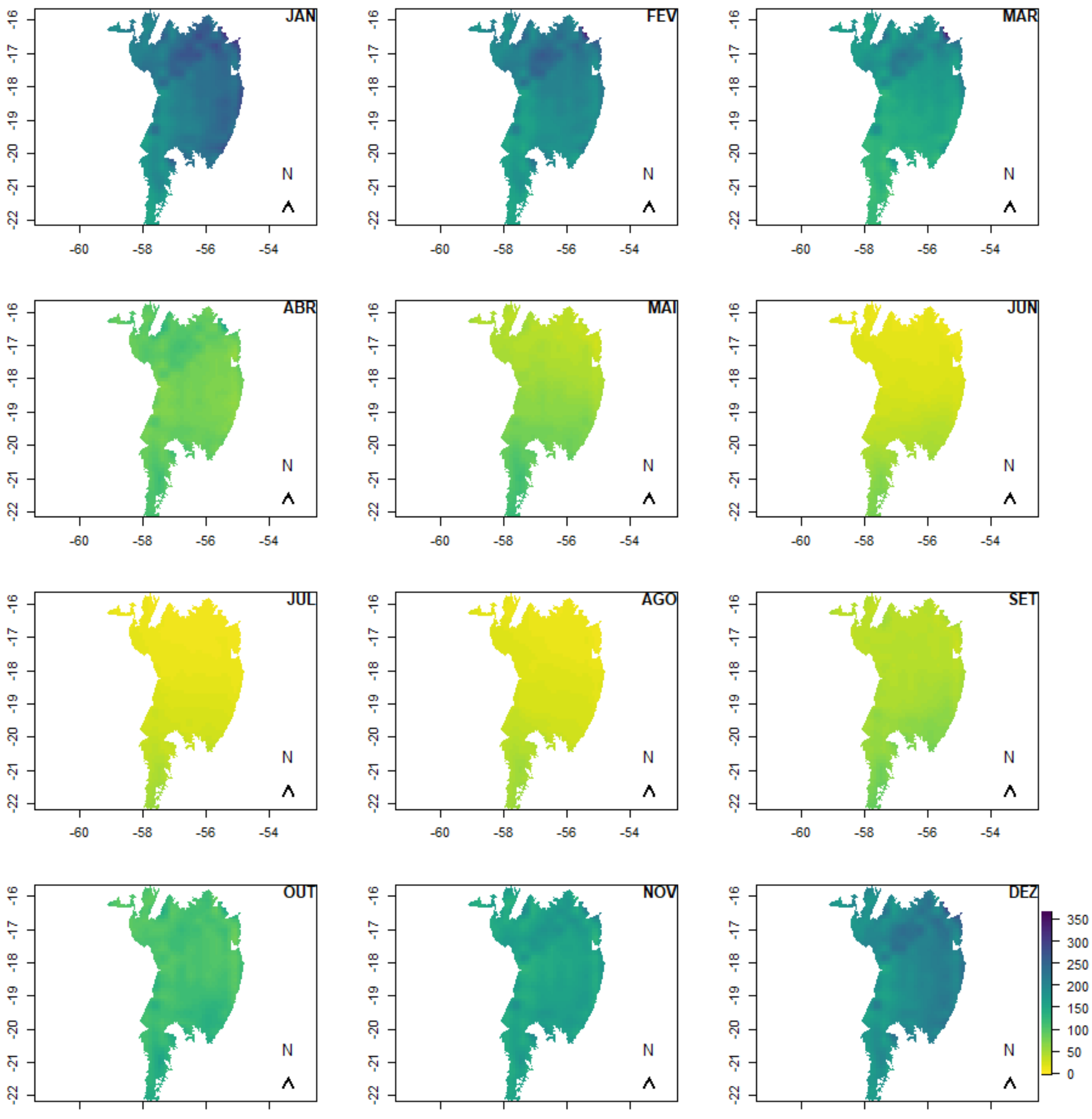

Figure 6 – Average monthly spatial distribution of rainfall in the Brazilian *Pantanal*, from 1994 to 2023.

The SPI-12 indicated different events within the historical series (Figure 7), with the characterization of exceptionally wet periods in some areas of the *Pantanal*, with positive indices fluctuating around 2.00 (SPI). This behavior was observed for several years; however, dry periods, classified as severely and exceptionally dry, are also distributed across different regions of the biome.

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ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 136 – 154, 8/2025
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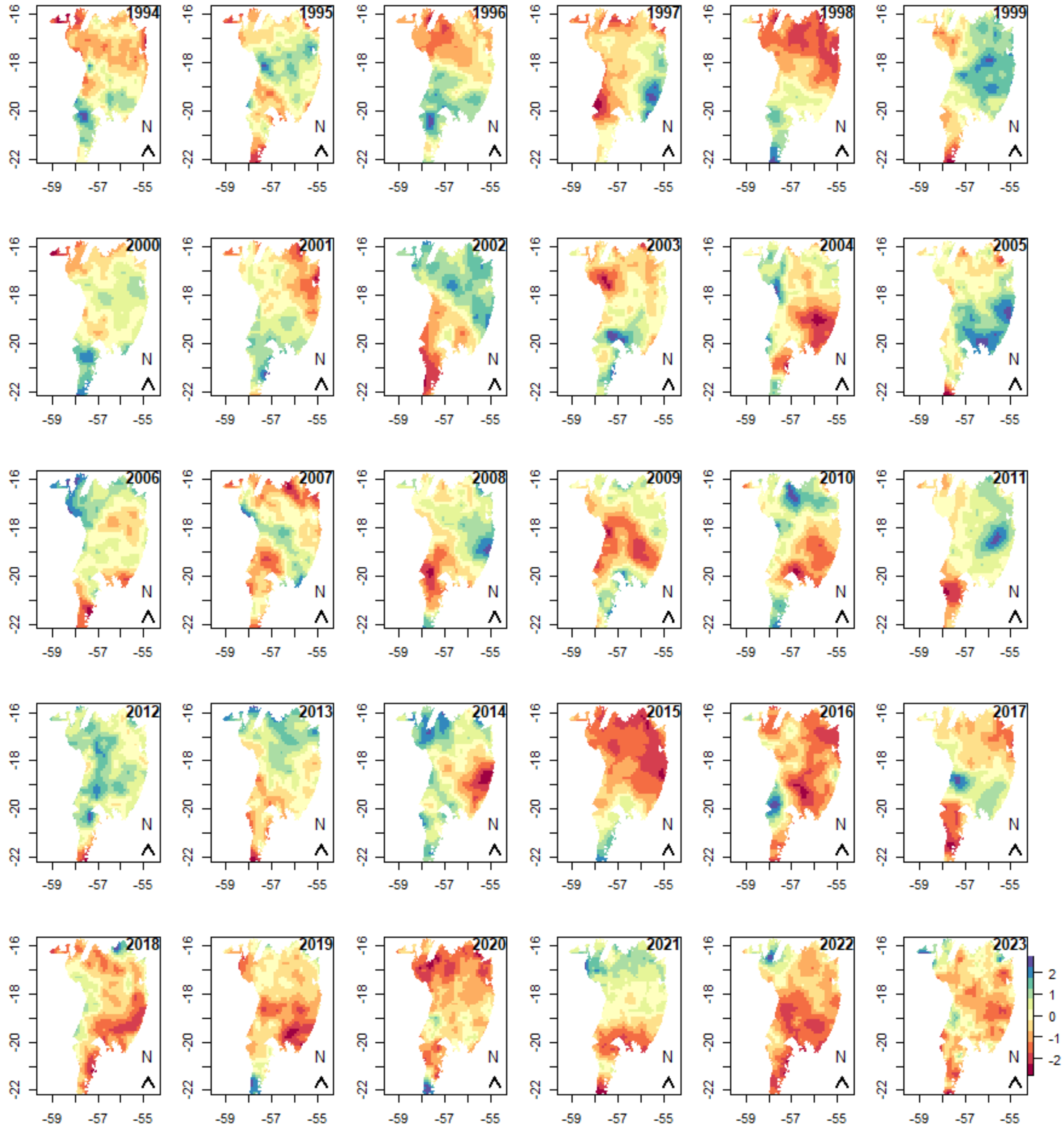

Figure 7 – Distribution of the SPI-12 for the Brazilian Pantanal, from 1994 to 2023.

Evaluating periods separately, from 1994 to 2014, there was an oscillation between dry and wet periods, concentrated in specific regions within the *Pantanal*, such as the 1998 drought in the North, 2002 in the South, and 2004 and 2009 in the central region. Additionally, during several years, some regions exhibited indices close to neutrality. In the period from 2015 to 2023, there was a higher concentration of dry periods, corroborating the annual precipitation distribution, which showed a precipitation deficit in the last few years.

These results indicate a greater prevalence of dry events in the last 10 years, a fact that may be associated with the regional precipitation regime, leading to instability and a higher occurrence of these

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episodes. The SPI identified significant drought events in the region, especially in the years 2015, 2019, 2020, and 2022, periods that are characterized by variability in different portions of the biome, covering *Pantanal* North, South, and Central, with some regions surpassing the -2.00 scale, classified as exceptionally dry.

Similar events were observed by Marengo et al. (2021), who analyzed the extreme drought in the *Pantanal* from 2019 to 2020 and characterized events similar to those observed in the present study. These authors, considering the period from 1900 to 2020, identified a fluctuation between wet and dry periods based on SPI-12 values. Nevertheless, they observed drought events concentrated mainly between 1962 and 1973 and from 2016 to 2020, which, according to the authors, coincide with changes in precipitation patterns, responsible for altering the water regime.

In a study of drought and heat wave events in the Brazilian *Pantanal*, Costa et al. (2023) observed similar results to those of the present study, identifying that the North and Central regions of the *Pantanal* underwent conditions of high temperatures and droughts during 2019. Furthermore, in the following years, the intensity and severity increased in other regions of the biome, reaching extreme levels in the North in 2020. In the same study, the authors also confirmed water stress in the region, especially from 2018 onwards, with more frequent extreme climatic events.

Similar results were also observed by Barbosa et al. (2022), who identified negative precipitation anomalies over two consecutive years (2019-2020). These conditions clarified the recurring drought events in the region. In the same work, the authors define that the entire Upper Paraguay Basin (*Planalto* and *Pantanal*) was warmer and drier in 2020, and moreover, the region's water regime has been decreasing annually.

According to the results of the present research, precipitation distribution in the *Pantanal* exhibits both positive and negative oscillations throughout the study period, with the notable feature that, from 2000 onwards, some years did not exceed the climatological average. This behavior may be associated with a possible change in the region's precipitation regime. These declines are more clearly indicated by the SPI, which determined different periods for the region, with significant droughts, especially from 2019 onwards.

Considering the spatial distribution, it was possible to analyze the precipitation behavior and drought events in different portions of the biome, identifying the North and Central regions of the *Pantanal* those with the most intense, severe, and frequent events. Furthermore, these regions exhibit both positive and negative oscillations in annual precipitation, a factor that could intensify the occurrence of extreme climatic events.

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IV. CONCLUSIONS

The annual average precipitation for the *Pantanal* is 1,536.66 mm, with particular emphasis on recent years, which have seen precipitation levels below the climatological average. The spatial distribution of precipitation, between 1994 and 2023, ranged from less than 1,000 mm to more than 2,500 mm, with a reduction starting in the year 2000, particularly in the last five years, when several regions of the biome recorded values below 1,000 mm.

The temporal analysis of the SPI revealed different events over time, with significant episodes in the years 2005, 2015, and from 2019 to 2023, presenting indices surpassing the -2.00 mark, and a trend line indicating an increased likelihood of drought events.

The SPI-12 indicated the alternation of dry and wet periods over the 30 years, with some periods being extremely wet and others exceptionally dry. However, between 2015 and 2023, a higher frequency of dry periods was observed, reflecting the reduction in annual precipitation and indicating a greater predominance of dry events.

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